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Instrumentation and Expert Systems
Software Integration for OMS
Leak Detection

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INSTRUMENTATION AND EXPERT SYSTEM SOFTWARE INTEGRATION FOR OMS LEAK DETECTION

1.0 Introduction

The use of single stage to orbit (SSTO) technologies to reduce the operations costs for the X-33/RLV programs provides the opportunity to reduce the recurring production and refurbishment costs associated with the present external tank and solid rocket boosters on Shuttle. However the implementation of SSTO dramatically increases the number of fluid components and complexity, which already represent the largest operational driver on the present Orbiter. Several system level technologies (i.e. common commodities, EMA's, etc.) have been recommended to help reduce these operations costs, however there is still a need to address the recurring costs associated with checking out the fluid components every flight or during standardized maintenance periods. This requires on the Space Shuttle a large number of test ports, quick disconnects and ground support equipment to accomplish individual component checkout.

With the increased emphasis and planning on the use of Vehicle Health Management (VHM) as a key to reducing operations costs on X-33/RLV there is a need for real-life applications in genuine flight and operational environments. In addition, with the realization that the Shuttle will be flying many years before an RLV would replace it, many of these technologies can be cost effectively retrofitted on the Shuttle. The following paper about Rockwell's "Fluid Mechanical Component with Built-in-Test" contract is part of NASA's Long Term, High Payoff program, a multi-year project for development of smart components required for automated checkout. A pneumatic and cryogenic testbed has been established at Kennedy Space Center to involve the operator integrally in the design of automated VHM systems. Addressed will be issues integrating an instrumented fluid system with a real-time software development tool for high fidelity leak detection and will explore the lessons learned from this integration, including but not limited to: Data acquisition and control fidelity, hardware and instrumentation selection, noise source location and filtration techniques and software analysis methods.
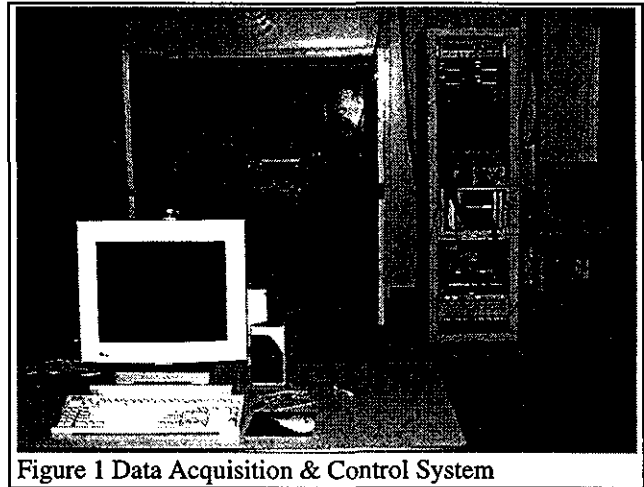

Figure 1 Data Acquisition & Control System

2.0 Problem

Characteristic of the normal post-flight checkout operations for a reusable vehicle such as Shuttle is the manpower and ground support equipment(GSE) intensive process for recertifying the vehicle for flight. The Shuttle OMS/RCS, which has some of the most stringent operational checkout requirements, was chosen to demonstrate the potential benefit of advanced IVHM technology. It is especially challenging due to its high degree of use of redundant components (and the need to isolate among them), the degree of other noise transmission sources, and the lack of sensors with the data resolution/response required for accurate and quick leak calculations. A particular challenge in this project was achieving the high fidelity of required sensor response and resolution currently achieved using the present manual processes performed with GSE, with on-board full range transducers. Our IVHM system automates test and checkout requirements for the OMS/RCS pneumatic systems that could take up to 1 week (2 shifts/day) and could require over 40 ground connections to the flight vehicle (QD mate, leak test each QD, etc.). Other challenges faced during the project are: Using valid data, at acceptable rates, integrated with a non-deterministic analysis tool and capturing this data from the instrumentation and its distribution to multiple checkout stations.

3.0 Approach

The project used a combination of qualification and flight hardware (a recreation of an OMS/RCS configuration) to demonstrate the feasibility of automating all maintenance required in the operational checkout of a pneumatic, high pressure system. Our research included ground checkout type configurations that can be implemented without the need for hook-up of external GSE. This involved integrating many differing instruments with a real-time software system and subsequently displaying and analyzing the data on a non-deterministic expert system.

4.0 VHM Checkout Panel Instrumentation

Using a combination of off-the-shelf(COTS) and advanced instrumentation, the first fully automated checkout of a pneumatic system has been developed and demonstrated at Kennedy Space Center. The testbed IVHM panel consists of a total
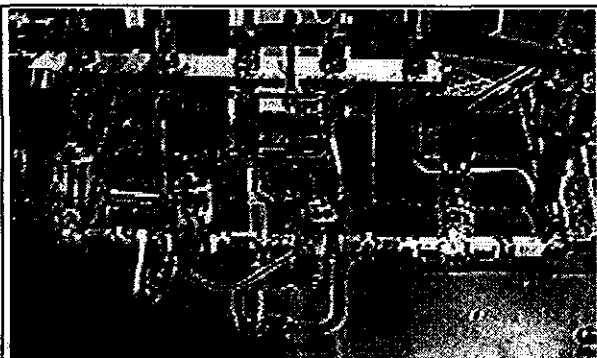

Figure 2. On-board Bias and Vent Control Unit (OBVCU)

of six solenoid valves, four temperature compensated, full range pressure transducers and three small flow control valves, routed to various components and a high-speed data acquisition system to enable us to perform automatic component checkouts such as forward isolation valve leakage, reverse quad-check valve leakage and other, previously manual, checkout requirements tests(see Figure 3.). These automated tests completely fulfill the OMRSD component checkout requirements in about one hour(versus one week, two shifts). These results can then be viewed at the test site, on a remote workstation and soon from any Internet web browser.

4.1 Transducers with RTD Compensation

One of the considerations, and ultimately a goal of IVHM is to reduce the number and complexity of fluid system components required for spacecraft system checkout. All leak rate calculations are based on a known volume and thus the temperature and pressure of that volume. By combining these two measurements into one component, we can save space and weight - two valuable elements in spacecraft design. Previously, traditional 100 Ohm thermocouples have been used for accurate temperature measurements. Alternatively, an 100 Ohm RTD can be inserted into the flow stream riding on the diaphragm of the pressure transducer and provide not only a compensated pressure value(over a specific temperature range), but can give a measurement of the in-line gas temperature. This compensated value should give us a greater fidelity of leak values during checkout and eliminate several connections, both fluid and electrical, in our system.

These high level output pressure transducers house the signal conditioning circuitry inside the transducer package. Onboard precision regulators derive a stable excitation for the strain-gage bridge, and the signals from the bridge are passed through an onboard amplifier which brings the transducer output signal level range up to 0-5 volts. This high level signal can be interfaced directly to an A/D board. The signal from the high level output transducers show a marked reduction to the effects of noise. Also, since any noise that occurs is much smaller relative to the actual signal level, filtering is much easier. This in conjunction with our improved data acquisition system allows us to achieve the very high data resolution required for leak checks using large range transducers (0-300 psis). The transducers used are "sealed" to hold a steady atmospheric pressure above the diaphragm and protect the signal conditioning electronics above it.

4.1.1 Results of Leak and Thermal Stability Instrumentation Tests

The quest for a complete pressure-temperature measurement package has recently gone unfulfilled. The current transducers tested were supposed to include inline gas temperature measurement along with its desired temperature compensation pressure reading but did not perform as requested. The on-board RTD was located inside the transducer casing and subsequently gave an accurate temperature of the transducer case only! A correction to this oversight has been developed by another manufacturer and we hope to test the new design soon. This configuration would essentially eliminate using thermocouples in our design, reducing not only weight and space but potential

leak paths, a driver to creating an on-board checkout unit.

4.2 Dual Port Valves

One of the concerns with applying IVHM was that the addition of numerous components and/or instrumentation sensors would to add to vehicle weight, increase complexity, and increase vehicle component failures. In addressing this it is first necessary to look at the existing method for checkout. For the OMS/RCS aft pod there is a checkout panel approximately 15 feet from the actual pressurization components. With the checkout panels/QD's on the other pods over 40 individual connections can be required during checkout. Each one must be leak checked and can obviously be a potential failure source. When addressed with the support GSE/facility which also has its own checkout requirements, failure potential, etc. the judicious addition of a few sensors can look favorable in comparison. There was still a goal to be weight neutral with the project, that is the weight of the checkout panel, QD's, support structure, lines, etc. (~ 12 lb. in the aft pod) which could be removed with the application of IVHM was approximately equal to the added weight of the IVHM system. We have simplified the OBVCU concept to something that could be deployed at under 10 lb. per pod. This was accomplished through the use of small, light weight solenoid valves. The Honeywell solenoid valves were chosen since they were reliable (600 cycles per minute - continuous duty), compact, and light weight (8 ounces) with high actuation speeds. (8 to 16 milliseconds). These low cost valves ($28/valve) are currently used in applications from vending machines to medical/dental equipment. Although the valve parts were chosen for their compatibility with hypergolics they still need to be verified in the operational environment before an accurate FMEA can be completed.

Offsetting the advantages we gained with using our OBVCU(see Figure 2), we encountered new challenges when tackling other checkout requirements involving other components. Especially those that require small delta pressures and a high degree of leak fidelity for accurate measure, i.e. a quad check valve. This component contains dual but separate flow paths, each containing two check valves or spring-loaded "poppets" designed to mitigate the flow of hypergolic fluids back into the helium system. Each poppet must be checked out at high and low pressures for verification of flow and calculation of

reverse leakage. This can be difficult to accomplish with full range pressure transducers and single flow-path valves. Current GSE configurations include small range delta pressure transducers with no temperature compensation or measure. This makes the accurate measure of leakage possible, but time consuming. The transducer, being such a sensitive device, is very susceptible to thermal changes and can give false readings(i.e. building air conditioning).

The current test procedures to checkout this component must include valves able to handle pressure on the inlet(from the on-board gas source) and the outlet (downstream regulated flow pressure). Our current solution did not provide this flexibility. It was determined that the small solenoid valves we have previously been using(See valves in Figure 2.) can be redesigned to hold flow in both directions, but at prohibitive cost for our research effort. Instead, slightly larger and heavier valves are being used that in effect double the weight of the valves and increase their space allotment by 1 1/2 times. Not meant for a permanent solution, they nonetheless provide an acceptable near-term plan for testing and development.

The other use for these valves will be to try to use a variation of pulse width modulation to eliminate the need for flow orifices that again add weight and space to the system. These orifices are currently used as "flow regulators" to high-pressure sensitive components. With an average seal life of a couple million cycles, part of the exploration will be to determine if this would be a feasible solution as opposed to fixed-sized in-line orifices or other methods of flow control.

4.2.1 Results of Valve Selection, Pulse Width Modulation and Flow Control

The results of using the larger, dual pressure port valves show that they do work as advertised. However they leak in certain configurations, the most secure(least leaky) position being upright and perpendicular to the flow. Some leakage, it is suspected, is caused by the choice of poppet seating material, a material named kalrez that stated by the manufacturer shortens valve cycle lifetime to 1 to 2 million cycles. (Kalrez is the only material that is compatible with both hypergolic substances that it may come in contact with during its normal life.) Pulse width modulation is possible but not practical with the volumes contained in the system. At the fastest rate, 16 milliseconds, a delta of 20 psi was observed inside the small volume of tubing leading

to the primary regulators. (This step is necessary to checkout the secondary regulators during normal serial checkout.) At this rate, it may be acceptable(albeit unecessary) to use the valves for this test, it certainly will not be useful for more precise pressure increments, such as in checkout for the quad-check valve.

The alternative to pulse-width modulation of solenoid valves is the use of flow control or orifices to attain the desired increment. In the case of checking out the vehicle quad-check valve, a flow test, low-pressure and high-pressure leak check are performed during OMDP. In order to perform these tests, in an on-board configuration, helium must be vented in small increments in order to achieve the required small delta across a poppet. Once the proper flow rate is determined through testing, a permanent orifice can be used that will save space and weight in an on-board unit.

4.3 Data Acquisition Concepts, Strategy and Lessons Learned

Part of choosing any instrumentation for our testbed involved matching it to a data acquisition system that takes full advantage of an instrument's range and sensitivity. During our initial phase of development, the acquisition system of choice are VME based products, including a signal conditioner for thermocouple and strain bridge excitation, an analog to digital (A/D) card for transducer inputs and a digital to analog (D/A) card for command and control signals. The current instrumentation is a mix of low level milliVolt and high level, 0 to 5V output transducers, some using excitation from the signal conditioner at +10V and the high level out transducers using the +28V bus from the power supply. Both transducers' signals are fed to the 12 bit signal conditioner or directly to the 12 bit or 16bit A/D board, depending on type and use. Inherent inaccuracies have been discovered in our original approach. For one, the signal received to the 12 bit board from some of the transducers are 'chopped' once for the sign bit, then chopped again for the board's -10 to +10 range, leaving about 25% of the range left for the actual measurement. This in conjunction with longer line lengths and improperly grounded boards create degraded signals and ground loop problems.

The resultant signal monitored included a fairly significant 'data toggle' that ruined any chance of measuring accurately the components with highly sensitive pressure differential requirements.

The first phase is to track down the noise generated by the system, either from the power supply, the board excitation, signal noise or EMF ground loop. We did find that the signal conditioner board itself created a generous amount of noise on top of its excitation. The transducer output signal however, was much quieter.

The second phase involves the data acquisition system upgrade. Results indicate that by routing the transducer signal to a 16bit A/D card with a 0 to 10V range, eliminating the path to the signal conditioner, the resultant measurement from both a high and low level pressure transducer is closer to linear by an order of magnitude or better. Previously the data toggle on a 0 to 5V transducer was approximately 2.0 psi, now is 0.02 psi. A little over half the signal fidelity is still lost(minus the sign bit) with the 0 to 10V board reading a 0 to 5V transducer.

Installing larger solenoid valves led to several discoveries about the state of our system. The 10 Watt coil (previously 6 Watt) contained in these valves changed our power requirements and justified using a stronger power supply. The use of a stronger supply found out a weakness we had in one of our MOSFET/relay configurations. A newly installed switch for an added valve did not contain an arc-suppressive diode and the ensuing inductive kick destroyed the FET gate quickly.

4.4 G2 Expert System Software and State Monitoring, Closed Loop Control

Our software development for real-time analysis and display uses the expert system tool, G2, developed by Gensym Corporation. This tool provides methods to create real-time displays and is capable of complex computation and analysis using a rule-based scheme, but also includes procedures and methods for sequencing and more traditional programming techniques.

The communications scheme of the software is to provide an acceptable interface to the data acquisition system broadcast data and to establish a link for command and control of component hardware, including valves, flow regulators, motors, etc. The analysis, and primary goal of the software is to provide real-time display, computation and state monitoring of the system. A tertiary and peripheral goal is to use the real-time data displays, rule-based analysis and data saving to track and explain real physical phenomenon occurring during checkout of the system and potentially report trends and predict failures. In addition, historical data saved during checkout operations is presented for post-analysis.

4.4.1 Real-Time Display, Data Plotting and GSI Command & Data Interfaces

During the development of any data analysis/control tool that has been 'touched by many hands' and iterated over the course of a few years, inefficiency and redundancy creep into the maturing product. Especially with an expert system that allows the developer to create rules whenever the need arises. Soon hardware resources are overextended and the analysis it was intended to perform is hampered by the computers need for resources to run the software.

Below are some lessons learned for creating an integrated hardware/expert system software tool:

1. Create the minimal amount of rules necessary .
2. Use rules only for event detection and minimal analysis. Avoid rules that fire every second(scanning).
3. 'Whenever' rules work better for display update and other event detection instead of scanning rules.
4. Use methods or procedures and a well structured class hierarchy to run redundant tasks. Rules take more resources to run repeatedly.
5. Use the data interface to run data averaging to relieve the software from performing the calculations internally.
6. Have the external data system drive the update of measurements to the expert system display, not vice versa. This relieves the software of seeking data updates for every sensor, every second.

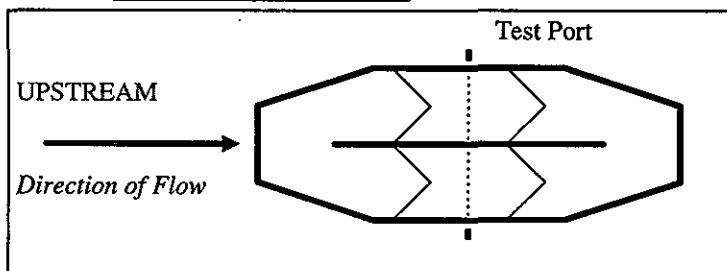### 4.4.2 Fluid System Debugging and Proactive Process Control

Figure 3. Quad Check Valve

The use of an expert system to track and control the checkout of a fluid system provides the necessary feedback to actually debug the process of checking out the system in question. The judicious use of plotting and display can show actual physical

phenomenon at work and can track down component imperfections and process abnormalities. An example: A quad-check valve is a dual-redundant path check valve with two poppets on each separate flow path in a closed package. (See Figure 3.) Its function is to prevent the flow of the propellant downstream to the helium system upstream. Safety dictates the dual path as one path may stick closed. A loss of helium to the propellant system dictates an aborted mission. Checkout requires that each poppet be verified for flow and tested for reverse high/low pressure leakage. While configuring the system to checkout each upstream poppet, we decreased upstream pressure by 100 psi and then proceeded venting through the test port on one side to achieve a delta across the poppet of not more than 3 psid. This would configure the check valve poppet for a low pressure reverse leak check. As the one side drained away, the other side of the check valve, completely separated internally, started to drain as well. Upon closing the vent (connected to the test port) the two sides started to equalize, with no change in pressure upstream or downstream of the check valve, eliminating the prospect of reverse leakage effecting the process. A plot of the rate of change in pressure on one side of the check valve vs. the other side revealed that the rates were equal and opposite, proving equalization. Testing in the same manner on the other side revealed the same behavior. The valves attached to the test port lines were found to leak, so the tests were repeated with the flow control valves(needle valves) closed completely (they do NOT leak) on each line, revealing the same behavior again. Draining the upstream completely and monitoring the pressures again did not change the results. After a few more induced isolation tests, it was concluded that the pressure could only equalize through the check valve internally! This must be proven by other means, but the expert system helped diagnose a problem component and may yet provide more evidence of how the system is behaving to produce this phenomenon.
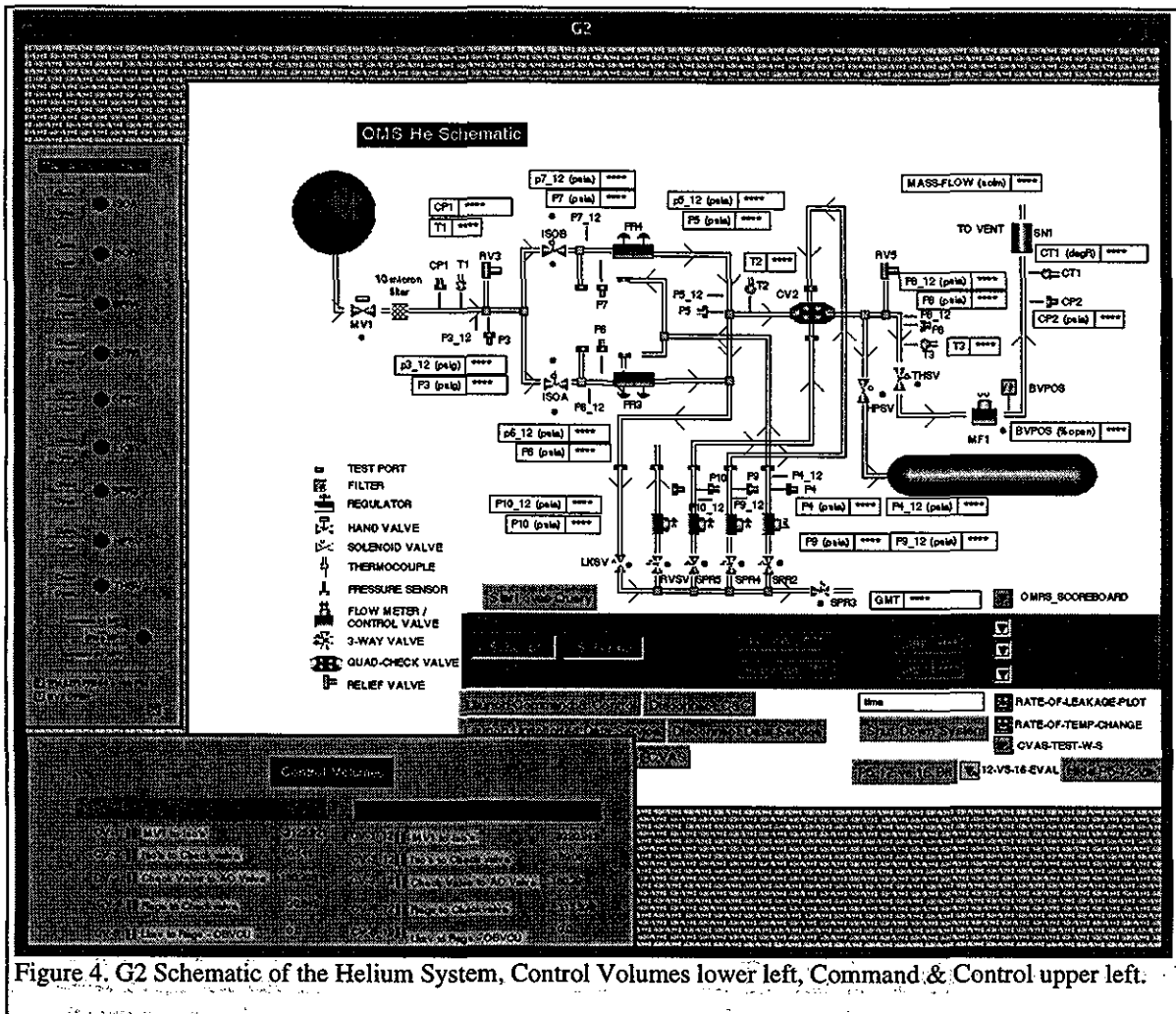
Figure 4. G2 Schematic of the Helium System, Control Volumes lower left, Command & Control upper left.

4.4.3 Real-Time Sequencing, State Monitoring and Closed Loop Control

Using the expert system gives a unique opportunity for state monitoring during component checkout. Previously the state of the system was determined proactively by the operator, essentially telling the software the current state during a sequence or was reported by visual inspection of measurements, and can lead to unrecoverable synchronization problems and resultant data error. The same goal can be accomplished by using the software. The display is already receiving data "real-time" from the instrumentation, so is then used by rules to actively determine a state. For example, while running a pressurization sequence, one temperature measurement goes off-scale high. This monitored measurement is reported as off-scale high to the operator and changes the state of the system to "Stopped On Error". This impacts the execution of the sequence by securing the system. This helps solve the problem of synchronization encountered

in sequence operations and provides a useful means to monitor a system without operator overload. Other state monitoring functions include determining the system gas state(flowing, static), current component under evaluation by watching valve states and measurement changes, pass/fail criteria for tests and data saving.

Some of the problems with existing sequencing operations is the "loss of signal", especially if a solenoid valve decides to prematurely expire. An alert operator could stop the system in its wayward path, but response time may be unacceptable in a tightly controlled process. Our current checkout operations are improved with closed-loop control mechanisms implemented in software routines. This is used in conjunction with state monitoring to control a sequence of operations. This is currently implemented in the display and analysis tool, but would probably be better suited to run on the deterministic kernel in the VME chassis.

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4.5 Leak Calculation

Performing leak calculations during checkout is one of the largest drivers of using IVHM to reduce serial checkout time. With a combination of instrumentation and automated procedures, this time can be reduced dramatically.

The G2 software is not entirely deterministic, as it relies on its own internal scheduler and clock to process its tasks. This makes the real-time display close to real time and is useful for operator monitoring. What is more useful, for leak calculations, is the rule-based analysis of the incoming data, and this is done by calculating the change in mass for a given volume, over time. Each part of the system is divided into several "control volumes"(see Figure 4), each containing its own pressure and temperature measurements, and a known volume. In addition, each control volume contains, or is divided by, the components that are the primary focus of the checkout procedure. For example, to calculate the leakage of the dual regulator, the mass differential of its parent control volume is calculated between the regulators and the quad check valve. This becomes useful later on for other components that may not have a close-by pressure or temperature measurement or if the leakage of one volume will affect another. Mostly the latter case is in effect for checkout operations. In the above example for regulator leakage, the reverse leakage of the quad check valve would be subtracted from the total leakage of the dual regulators. A combination of automated software

and data acquisition equipment is necessary to obtain accurate leak curve data. Current operations require a waiting period for thermal stabilization and then another waiting period for leak stabilization. This process can take up to 15 minutes or even hours to accomplish, depending on the instrumentation and component of interest. If the leak is performed out of thermal stability, the test is failed and must be repeated. The best way to reduce the amount of time required to obtain an accurate measure of a leak is to a) increase the data acquisition system fidelity, b) eliminate any source of noise transmission, c) increase the total accuracy and repeatability of the instrumentation and d) use software to calculate thermal stability points and leak linearity points. Procedures in the expert system perform the necessary steps for d). Thermal stability is obtained by watching the control volume temperature measurement of interest and waiting for the slope of the curve of the rate of change to approach 0.0, within a tolerance band. Once achieved, leak testing begins and again is watched until the rate of change approaches 0.0. Coupled with the data acquisition system, results indicate that leak stabilization is achieved faster with 16 bit data than 12 bit data. This follows the preliminary calculations done prior to 16 bit installation, that concludes 16 bit data should decrease leak time substantially. However, with noise riding the 12 bit signal from the signal conditioner already, 12 bit data was less accurate in the beginning.

Figure 5. Leak Calculation Rule. Fired every second.

Operational results show the resultant leak curve is also affected by the ambient room temperature (i.e. air conditioning cycles) and was repeated in the laboratory. Leak checks are usually done with thermally sensitive delta pressure transducers on the order of 0 to 15 psid. Full range, temperature compensated pressure transducers may solve this inaccuracy.

5.0 IVHM for the Checkout Data Acquisition and Control System

A major issue that must be considered by any health management system is verification of the health of the data acquisition components. At the OMS IVHM testbed this includes various types of sensors, cabling, signal conditioning, signal converters, processor boards, and power supplies. Some of the techniques include:

1. Using pressure transducers built with shunt connections that allow a precision resistor to be jumpered across one arm of the strain-gage bridge. This test verifies the pressure transducer cabling, as well as, continuity through the four arms of the transducer itself.
2. Automatic calibration of the signal conditioning equipment is accomplished using self calibration techniques that allows for complete, routine, automatic calibration and automatic zeroing of the data

acquisition system front-end as well as automatic testing of the +5 volt and +/- 12 volt power supplies of the VME chassis.

3. The health of the CPU boards, networks, and any other support boards are verified using a mixture of hardware Built-In-Test (BIT) techniques and additional customized software routines

4. Any network connection used for control undergoes a test for proper operation using a command-response technique with special health checks

6.0 Summary of Important Conclusions

As prior to this work no pneumatic system on a launch vehicle had ever been fully automated. This project demonstrates the feasibility of fully automating even a heavily redundant system using vehicle health management. Some of the conclusions reached to date:

1. Smart instrumentation coupled with advanced software techniques dramatically can reduce serial fluid component checkout time with greater accuracy.

2. Properly tuned and configured data acquisition equipment plays the vital role in measurement analysis in software.

3. Expert system software provides unique opportunities to analyze data more efficiently and effectively to monitor the conditions of a fluid system.

4. Software can reduce the time necessary to perform fluid component leak checks with auto-determination of thermal and leak stability points.

5. Valve seating material must be selected carefully to be compatible with both hypergolic fluids. The sealing material requires further study to determine the best configuration to eliminate leakage through the valves.

6. High fidelity instrumentation and expert system software can help debug a fluid checkout process and identify process and component anomalies.

7. IVHM technology, integrated properly into the design of a system, can potentially reduce long term operational and maintenance costs.

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